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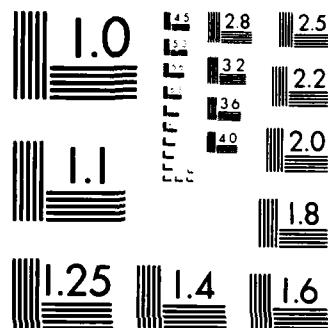
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FINAL REPORT
TO
OFFICE OF NAVAL RESEARCH

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RESEARCH ON OCEAN FLOOR ELECTRICAL SURVEYS

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ABSTRACT

An important problem faced by the U.S. Navy is that of detecting submarines at greater ranges with airborne magnetic sensors than can now be done. One of the limits to the range at which detection is possible is the confusion of submarine-generated signals with natural-field pulsations of the earth's magnetic fields. One approach to the removal of the natural magnetic noise is that of monitoring the fluctuations of the earth's natural field at a base station, and making corrections at a moving airborne system. This requires two assumptions: the magnetic field of variations are coherent over the range on which cancellation is accomplished, and the correlation between magnetic field effects at the two sites is not dependent on the geology at either the mobile station or the reference site.

Experience with geophysical surveys indicates that coherency of the magnetic field does exist; but, also, in water depths up to several thousand feet, the magnetic field is dependent upon geology at the observation site. This leads to a requirement for a method to evaluate the effect of subsea geology on local micropulsation behavior. In the research described in this report, three general categories of subsea electrical surveys were reviewed: direct current resistivity surveys, magnetotelluric soundings, and seafloor based electromagnetic system.

In our review, we have concluded that the electromagnetic method offers the most promise for providing information on subsea geological effects, but that development of equipment will be difficult and expensive.



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INTRODUCTION

One of the principal means for locating submerged submarines is through the use of airborne magnetometers. The distance at which the magnetic field from a submarine can be detected is limited by the background noise, a large part of which now comes from natural field micropulsations of the earth's magnetic field. The level at which the signal from a submarine could be recognized and, therefore, the distance at which a submarine can be detected, could be increased if the submarine-caused signals could be separated more effectively from the background of micropulsation noise. One approach to such separation is that of monitoring the fluctuations of the earth's natural field at a base station, and use of a data link to transmit corrections to the mobile airborne system. This approach requires two assumptions:

- 1) Magnetic field variations must be coherent over the range on which cancellation is accomplished.
- 2) The correlation between magnetic micropulsation field effects at the two sites is not dependent on the geology at the mobile station.

In recent years, the coherency of micropulsations over ranges of tens to several hundred kilometers has been studied extensively in the application of the magnetotelluric method, where the current standard practice is to carry out observations of two or three sites simultaneously. This provides data necessary to compute the coherency of the magnetic field variations at these sites. As an example, Fig. 1 shows the coherency between magnetic field variations at two sites in northern Arizona separated at a distance of 110 kilometers. Coherency here was defined as the rms difference between the magnetic field vector observed at site B, \vec{H}_B , and that computed from the magnetic field vector observed at site A, corrected by the transfer function T_{ij}

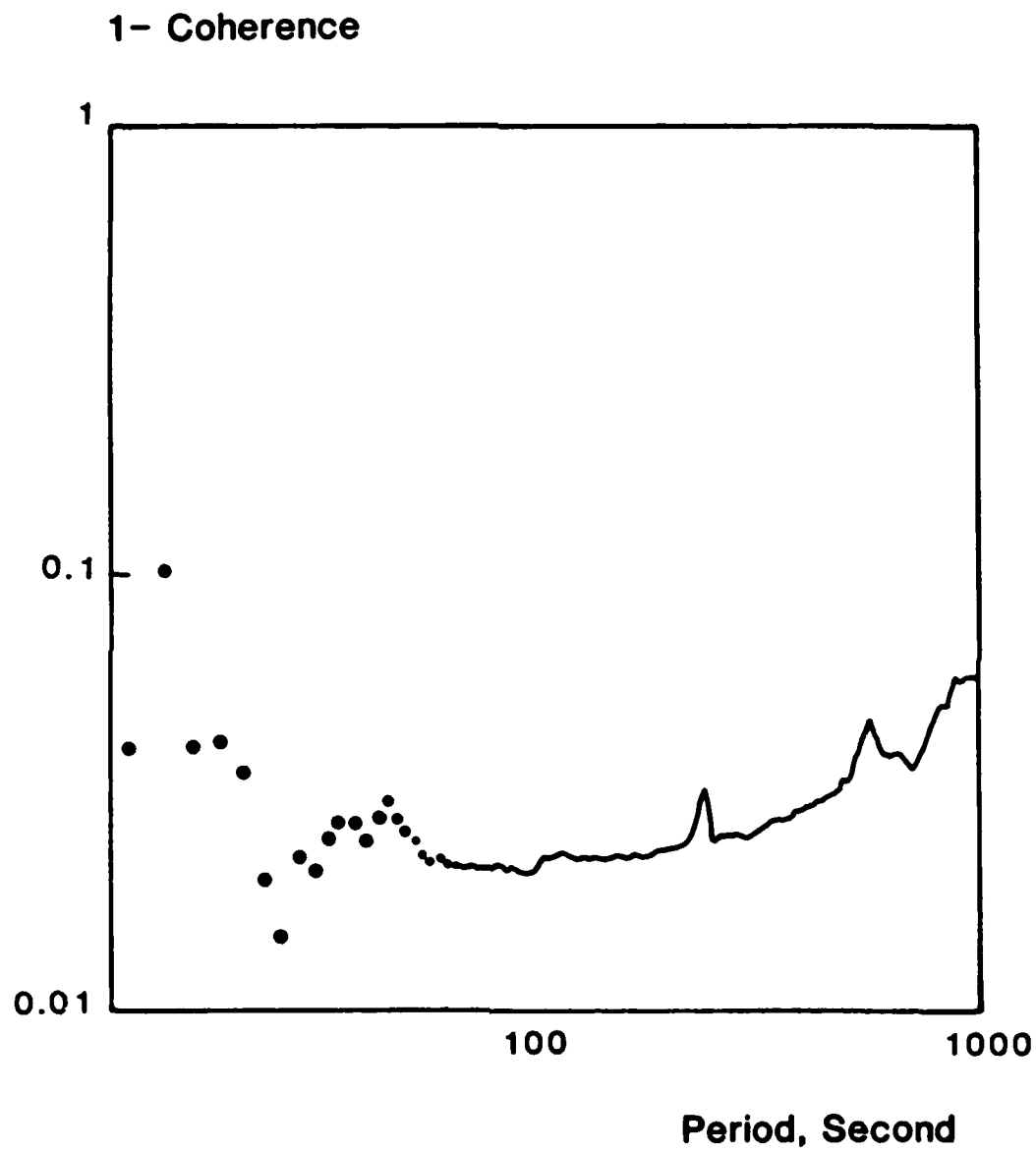


Figure 1. Incoherency (1-coherency) for two magnetic field vectors observed at sites located 110 kilometers apart in northern Arizona.

representing the effect of geology at the two sites on the magnetic field. Over the range of interest, the coherency is 95% or better; the field at site B could have been reduced to 5% of its observed level by using the transfer function T_{ij} to cancel it with the field observed at site A.

Fig. 2 illustrates the fact that the magnetic signal created by a submarine resembles natural oscillations in the micropulsation field of the earth. The submarine signal varies spatially while the micropulsation signal varies in time, but because the airborne sensor is moving through the spatial variation of the submarine field, the submarine signal is converted to a time-varying signal that can be confused with micropulsations. The relationship between spatial frequency and temporal frequency will depend strongly on two factors: the distance of the aircraft track from the submarine, and the speed of the aircraft. As an example, Fig. 3 shows the temporal period of the signal from a submarine 500 meters distant from an aircraft, flying at speeds ranging from 30 knots to 540 knots.

The micropulsation field of the earth results primarily from electrical currents in the upper reaches of the ionosphere and magnetosphere. These currents in turn are excited by the interaction between solar plasma arriving at the earth and the magnetic field of the earth. The excitation by the solar plasma is probably random in character and generates a wide spectrum of frequencies. However, the physics of the reaction with the ionosphere may favor some frequencies over others and, as a consequence, the micropulsation magnetic field that we see at the surface of the earth appears to be dominated by several frequencies. Among these is a frequency band from .025 to .050 Hertz, a type of micropulsation named PC3. This particular micropulsation bears the closest resemblance to a submarine-generated signal, and so is the primary background noise of concern in developing a more sensitive system.

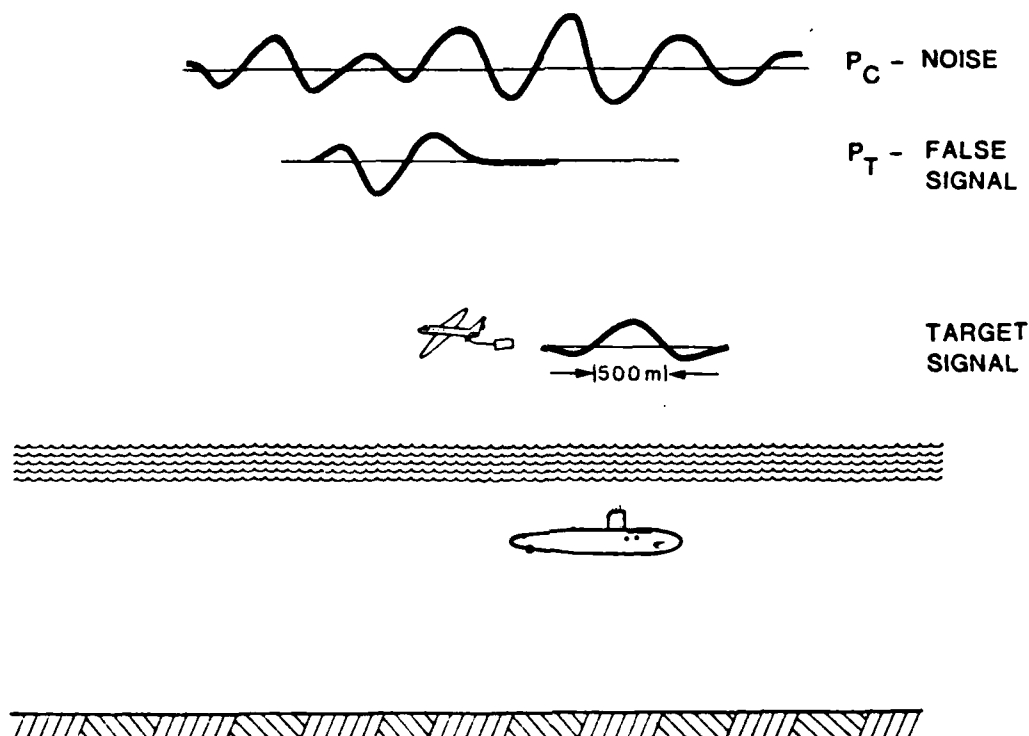


Figure 2.

Time varying magnetic effects seen with a moving aircraft. Natural signals may be continuous pulsations (PC) or transient pulsations (PT). Very similar temporal responses will be seen as the aircraft moves through the spatially varying magnetic field of a submarine.

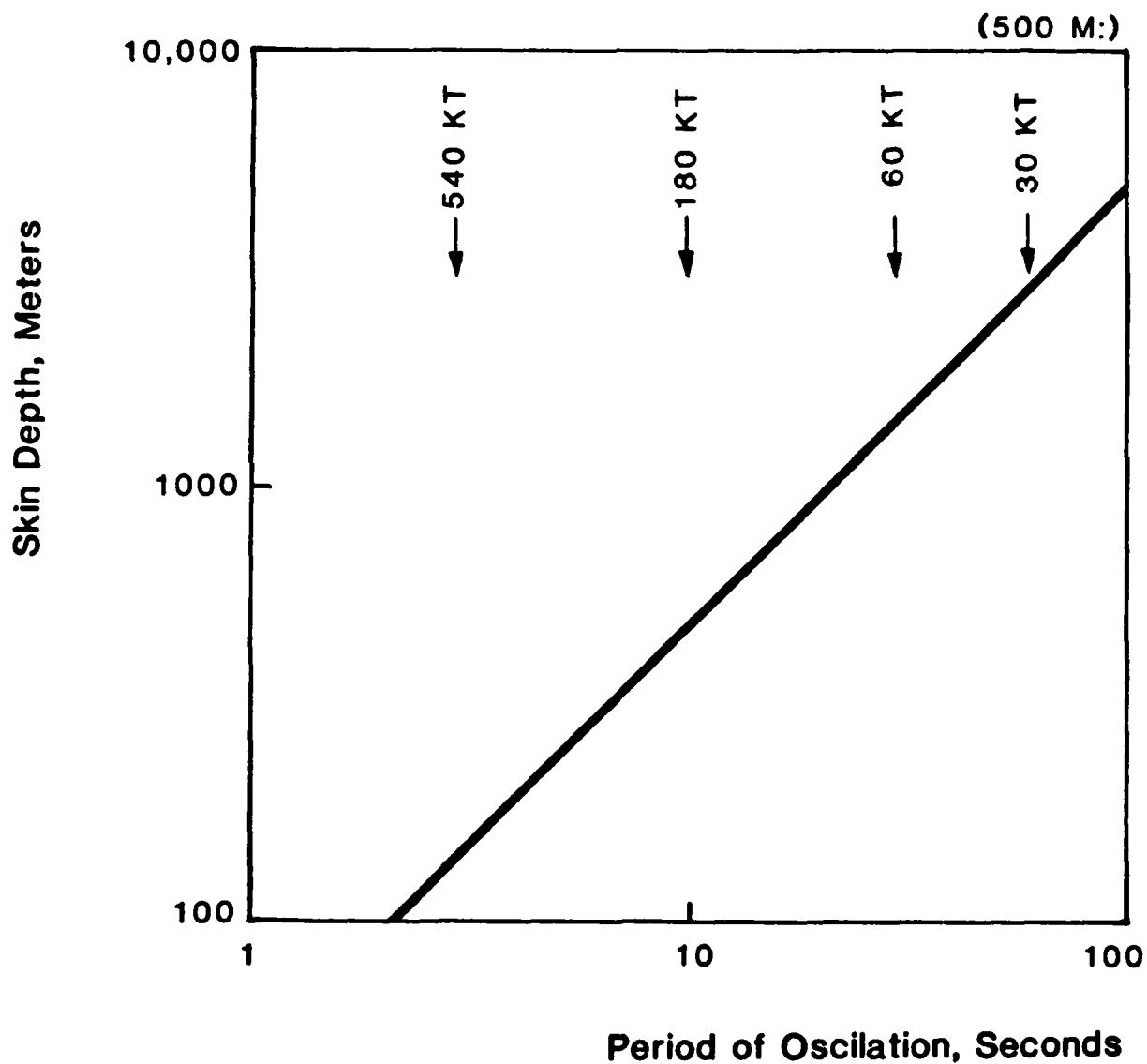


Figure 3. The temporal period of the magnetic field effect from a submarine as an aircraft passes along a track that comes within 500 m of the submarine. The period depends on aircraft speed, indicated in knots.

The PC3 micropulsation field is generated by a large-scale current distribution at elevations of thousands of kilometers above the earth's surface. As a consequence, when the magnetic field from these currents is viewed on the surface of the earth, they are expected to be uniform over broad areas, perhaps amounting to hundreds of kilometers or even several thousand kilometers.

The earth is not uniform in its electrical characteristics and, therefore, varying current densities are induced in the earth at different locations as a consequence of the arrival of the micropulsation field on the surface. These currents induced within the earth have secondary magnetic fields associated with them that combine with the primary field arriving from outer space when a survey is made at the earth's surface. An important question is that of the behavior of the total field as opposed to the uniformity behavior of only the incoming field.

The total magnetic field at the surface will consist of two parts, an incoming part which may have three components and a phase structure, and a reflected part which may also have three components and a different phase structure. The combined fields can then be represented as

$$\vec{H}_T = \vec{H}_1 + R\vec{H}_1 = \vec{H}_1 + \vec{H}_2 \quad (\text{Eq. 1})$$

where H_1 is the incident magnetic field,

H_2 is the secondary magnetic field caused by currents within the earth, and

R is a reflection coefficient.

The reflected magnetic field will most commonly be changed in direction because the conductivity of the earth is anisotropic, and so varying amounts of current density will be generated by the incident magnetic field in the various directions at which it arrives. The secondary magnetic field will also differ in phase with respect to the primary

magnetic field. Therefore, the reflection factor is a complex three-component tensor. The process of reflection of the incoming magnetic field is a linear process, so that despite the complexity with respect to spatial and temporal orientation of the total field, at least the total field will be proportional to the strength of the incident field.

If one wishes to compare the micropulsation field at two different locations so that the observation at one location can be used to cancel the field at the second location, there will be a reflection coefficient appropriate to each of the two locations. These must be known in order to accomplish the cancellation. Moreover, if the field is to be cancelled in real time, the reflection coefficient, which represents the geologic structure beneath the observation site, must be known beforehand. There will not be time to observe a long series of oscillations and calculate the transfer function which represents the relationship between the magnetic field at one location and that of another:

$$\vec{H}_A = T_{ij} \vec{H}_B \quad (\text{Eq. 2})$$

where T represents a transfer function for any two sites, incorporating the reflection factor at each of the two sites, and

H_A and H_B are the total magnetic field vectors observed at sites A and B.

Fortunately, in the search for submarines in deep water, the ocean can be considered to be a uniform conductor with no anisotropy and, therefore, the reflection coefficient for one site is known quite accurately beforehand. The reflection factor for the reference site, which might be located on shore, is a quantity that can be determined through careful measurement beforehand and which will not change with time. Therefore, if these two conditions are met, it seems reasonable that a shore-based station can be used to cancel the micropulsation background level at a moving station over deep water.

Skin depth is defined as

$$\delta = \left(\frac{2}{\omega \mu \sigma} \right)^{1/2} \quad (\text{Eq. 3})$$

where ω is frequency in radians per second,

μ is magnetic permeability, and

σ is conductivity (about 4.0 for sea water).

At a nominal frequency of a submarine-caused signal of 0.10 Hertz (see Fig. 3), skin depth in sea water is 890 meters. When the sea floor lies at a depth of one skin depth (890 meters for a ten-second signal), the effect of sea floor geology on the reflected magnetic field is barely detectable. For lesser water depth, the effect of the bottom becomes progressively more important, dominating the reflection coefficient for the magnetic field at water depths less than 1/2 skin depth (445 meters at 10 seconds).

The problem addressed by the research being considered here is that of how best to determine seafloor electrical structures, so that the degree of interference caused by such structures in shallow water can be predicted, and possibly compensation can be determined. Methods for determining electrical structures on land are well developed and well known (Keller and Frischknecht, 1966; Kaufman and Keller, 1981, 1983, 1984). Determination of subsea electrical properties is a very much different problem. While some theoretical and experimental work has been done in the past, no routine method for surveying subsea is available. The presence of a thickness of highly conductive seawater which tends to absorb electromagnetic field energy makes the problem of driving energy into the seafloor particularly difficult. Therefore, the objective of the research being reported here was to review the options that might be available and recommend one for possible experimental use.

METHODS AVAILABLE

Electrical resistivity of the earth can be surveyed in a great variety of ways. For the sake of classification, we will here describe three groups of methods--these being direct current (DC) methods, magnetotelluric (MT) methods, and electromagnetic (EM) methods. Each of these could conceivably be used in surveys of ocean floor electrical properties.

The DC Method:

Direct current methods have been used to a greater extent in marine exploration in the past than any other technique. In the usual application of a DC method, four electrode contacts with the earth are used. Current is driven through one pair of electrodes, and the potential generated by the current is measured with the other pair. Under favorable conditions, such measurements can be used to evaluate the electrical resistivity in the rock beneath the array of electrodes to a depth comparable to approximately half the total dimension of the electrode array. In marine operations, the procedure which has been used extensively is to tow an array of electrodes with fixed spacing. The theory for such marine DC measurements has been published by Terekhin (1962).

A difficulty is encountered with the use of direct current methods on the sea because, in most circumstances, the seawater itself is much more conductive than the seafloor, and the current field will tend to stay primarily within the sea. In order to obtain penetration of enough current into the seafloor to test its properties, electrode arrays with dimensions of ten times the sea depth, or even more, are required. When such large arrays are used, the seafloor conductivity is averaged to comparable depths beneath the seafloor. As a result, conventional DC electrical methods are "blind" to the properties of the immediate seafloor to depths at least several times as great as the sea water depth.

Modified DC electrode arrays may have promise for improving the response of DC measurements in the blind zone. In such methods, an attempt is made to detect the leakage current through the seafloor; such a system has been described by Edwards and others (1984).

The Magnetotelluric Method

In the magnetotelluric method, the natural electromagnetic noise field of the earth at low frequencies is used to study the electrical structure (Filloux, 1979; Kaufman and Keller, 1981). The same micro-pulsations that comprise the noise background in submarine detection are used because they give rise to the induction of electric currents in the conductive parts of the earth. The more conductive a region is, the higher will be the current intensity. By measuring simultaneously the variations in electric field strengths caused by currents flowing in the earth in the magnetic field strengths which generate these currents, it is possible to determine the electrical structure of the subsea.

In the magnetotelluric method, frequency of the natural electromagnetic field is used as a parameter to specify the depth of investigation. Relatively high frequencies penetrate only to the relatively shallow depth in the area, while lower frequencies penetrate to greater depths. The depth of penetration of the electromagnetic field is characterized as a skin depth.

However, with a half kilometer of sea water lying between the measurements system and the rock whose resistivity is to be determined, the ability of the magnetotelluric method to recognize the resistivity immediately beneath the seafloor is impaired. Again, the transition between those frequencies for which the seawater affects the measurement and those which clearly indicate the sea bottom creates a blind zone for a region beneath the seafloor which is several times as thick as the sea depth. Therefore, as with the DC method, in the magnetotelluric method

the sea water effect screens the response that should come from the rock immediately beneath the seafloor.

Since the magnetotelluric method senses only what lies beneath the measurements system and not what lies above it, one way of getting around this problem is to deploy the equipment on the seafloor (Hermance, 1969). Making magnetotelluric surveys with the equipment deployed on the seafloor is difficult, not only because of the operational problems but also because the motion of the sea can give a noise background which prevents making reliable measurements at frequencies lower than .05 or less (Cox and others, 1978; Cox, 1971; Moose and others, 1974). However, if measurements are to be made at great depth beneath the seafloor, some success has been enjoyed at frequencies ranging from .05 Hertz down to .001 Hertz (Chave and others, 1979; Poehls and Von Herzen, 1976).

The Electromagnetic Method:

A promising method which is still in an early stage of development has been the primary subject of research in this effort. The use of electromagnetic methods has been explored theoretically, and to some extent experimentally, by Bannister (1968); Mathews (1970, 1973); Shaub (1978); Cox and others (1979, 1980, 1983); Young and Cox (1981); and Edwards and others (1981). Although the electromagnetic method is less well developed than the magnetotelluric method, and apparently requires a more complicated operation for its success, it shows considerable promise because relatively high-frequency signals can be transmitted into the seafloor, and the properties can be measured with good resolution. In the research which was carried out as part of this project, we considered the essential features of the behavior of the electromagnetic field in a conducting medium which would permit us to choose the frequency range over which the influence of the sea water can readily be taken into account. A variety of transmitter and receiver geometries can be used, probably with equal success; but for the numerical efforts in this research, we have restricted our attention to

the case in which the transmitter for the electromagnetic field is a vertical magnetic dipole (a loop of wire lying on the seafloor), and the receiver is a grounded line also lying on the seafloor (see Fig. 4). Later, in experimental work, we used a receiver consisting of an ungrounded loop rather than a grounded wire. Only the frequency domain was considered, but conversion to the time domain is a trivial extension of the theory.

The behavior of the electromagnetic field can be derived simply from solution of Maxwell's equations. In the frequency domain, with a field varying as $e^{-i\omega t}$, these equations are:

$$\begin{aligned} \text{curl } \bar{E} &= i\omega\mu\bar{H} & \text{div } \bar{E} &= 0 \\ \text{curl } \bar{H} &= \sigma\bar{E} & \text{div } \bar{H} &= 0, \end{aligned} \quad (\text{Eq. 4})$$

where \bar{E} and \bar{H} are the the electric and magnetic fields, respectively,

$\omega = 2\pi F$ is the radian frequency, and

σ is the conductivity.

We will seek a solution using only the vertical component of a vector potential \bar{A}^* defined as

$$\bar{E} = i\omega\mu \text{curl } \bar{A}^* \quad (\text{Eq. 5})$$

By substitution of this expression for vector potential into Maxwell's equations, and solution of these equations by the usual separation of variables approach, we arrive at the equation for the vector potential on an n-layered medium beneath the seafloor as follows:

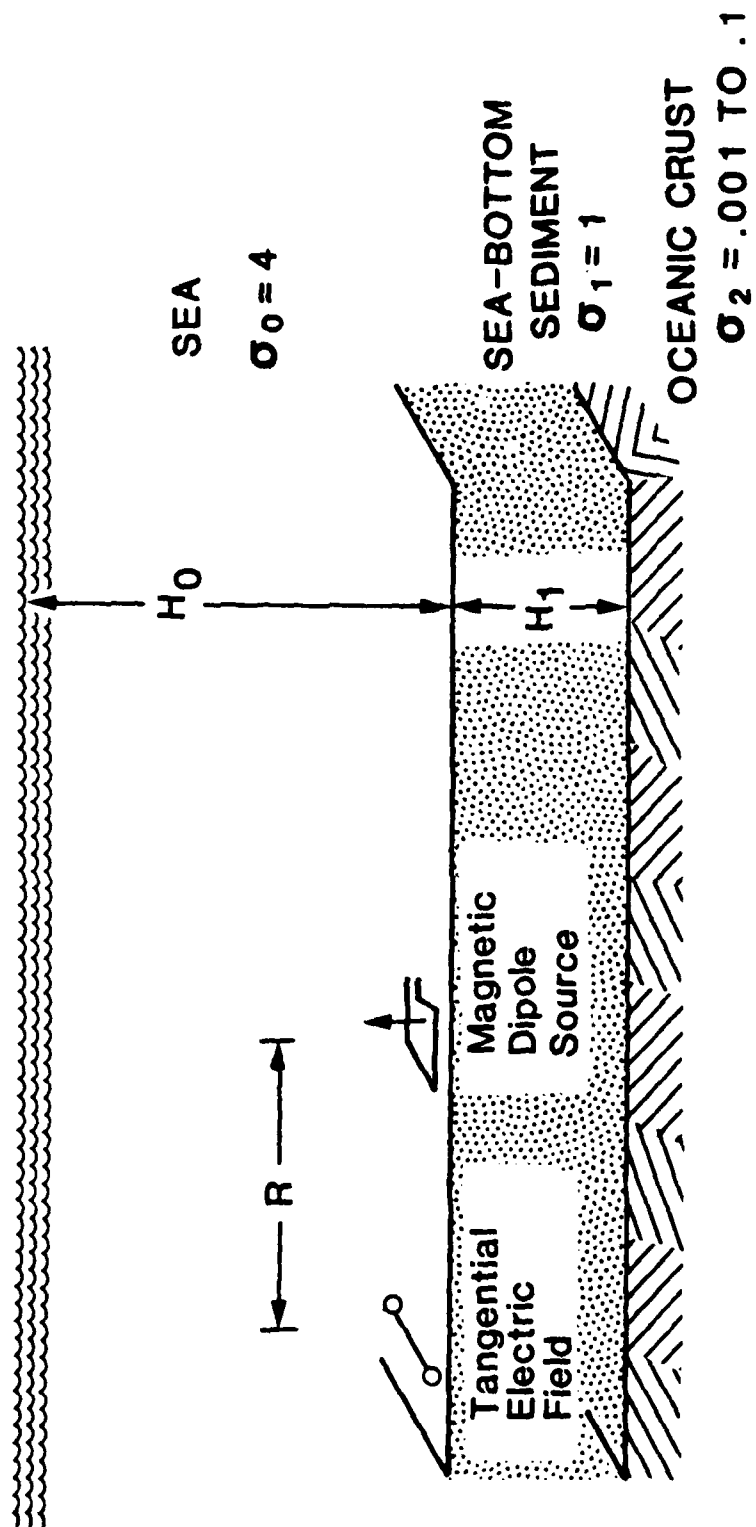


Figure 4. Transmitter-receiver geometry assumed for calculations of seafloor response to EM probing.

$$A_z^*(0) = \frac{M}{4\mu} \int_0^\infty \frac{m}{m_0} \left(1 + \frac{m_0 R_n - m_1}{m_0 R_n + m_1} e^{-2m_0 d} \right) J_0(mr) dm, \quad (\text{Eq. 6})$$

if $z = 0$ (at the seafloor)

where d is the height of the source above the seafloor,

$$m_0 = \sqrt{m^2 + k_0^2}, \quad k_0 = \frac{1-i}{\delta_0}, \quad \delta_0 = \sqrt{\sigma_0 \mu \omega}, \quad \lambda_0 = 2\pi\delta_0.$$

(Medium 0 is seawater and M is source moment, the product of area and current of the source loop.)

The quantity R_n is a correction of the factor representing the effect of an n -layered seabed on the vector potential, A_z^* :

$$R_1 = 1 \text{ for a half uniform space beneath the seafloor;} \quad (\text{Eq. 7})$$

$$R_2 = \coth \left[m_1 h_1 + \text{arc coth } \frac{m_1}{m_2} \right] \quad (\text{Eq. 8})$$

for a two-layered medium beneath the seafloor,

$$R_3 = \coth \left[m_1 h_1 + \text{arc coth } \frac{m_1}{m_2} \left\{ \coth m_2 h_2 + \text{arc coth } \frac{m_2}{m_3} \right\} \right], \quad (\text{Eq. 9})$$

and so on.

where h_1, h_2 , etc. are the thicknesses of the layers in sequence beneath the seafloor, and

m_1, m_2 , etc. are modified wave numbers similar to that defined in Eq. 6, except that σ_1 is substituted for σ_0 .

The evaluation of an integral such as given in Eq. 6 is straightforward using either convolution or spline fitting techniques.

The asymptotic behavior of the field provides insight into how a subsea electromagnetic sounding system should be designed. Let us assume that the source and the receiver are situated at the interface between two uniform half spaces, one having the conductivity of seawater, and the other having the conductivity of the seafloor. The expression for vector potential at the seafloor can be written as an exact solution with elementary transcendental functions:

$$A_z^* = - \frac{M}{2\mu (k_0^2 - k_1^2) r^3} e^{-k_0 r} (1 + k_0 r) - e^{-k_1 r} (1 + k_1 r) \quad (\text{Eq. 10})$$

where r is the distance from transmitter to receiver.

This relatively simple expression reveals interesting features which are valid even for more complicated models of the medium. Expanding the right hand side of Eq. 10 in a series of powers of the small parameter $k_0 r$ or $k_1 r$, we see that in this case, a) the primary field prevails, and b) the secondary field is defined mainly or almost entirely by induced currents in the more conductive medium; that is, in the sea water. In other words, at low frequencies, measurements will not provide any information about the conductivity in the seafloor. This fact is easily explained from a physical point of view and remains valid for any layered medium beneath the seafloor when these layers are more resistive than water, and when the depth is great enough that the sea can be representative of being a half space.

As our next approximation, we should consider large values of r or, more exactly, the case in which the wavelength in sea water,

$$\lambda_0 = 2\mu\pi_0$$

is less than the separation, r :

$$\frac{r}{\lambda_0} > 1.$$

Eq. 10 suggests that energy arrives at the observation site along two independent paths, namely:

- 1) Through the upper half space along the interface;
- 2) Through the more resistive medium, also along the interface.

Both parts of the energy decay in proportion to the exponential term

$$e^{-kr} = e^{-r/\delta} e^{i r/\delta}.$$

If $\frac{r}{\delta_0} \gg 1$ and $\sigma_0 \gg \sigma_1$,

the field is defined mainly by the part of the energy which arrives through the resistive medium. In this case, in accord with Eq. 10 we have

$$A_z^* = \frac{M}{2\pi k_0^2 \left(1 - \frac{\sigma_1}{\sigma_0}\right) r^3} e^{-k_1 r} (1 + k_1 r) \quad (\text{Eq. 11})$$

$$\text{if } \frac{r}{\delta_0} \gg 1, \sigma_0 \gg \sigma_1.$$

It is important to recognize that for large values of r/δ_0 , the influence of the conductivity of the sea does not depend on the separation r , and it can easily be taken into account. Also, the frequency response is defined by the parameter r/δ_1 ; that is, by the conductivity in the more resistant medium. This consideration indicates that the operation of a system at large values of the parameter r/δ_0 can provide optimum results in removing the effective seawater and providing the greatest depth of investigation into the seafloor.

To see this more clearly, we must derive an asymptotic expression for the field in the horizontally layered medium, corresponding to values $\frac{r}{\delta_0} \gg 1$.

For determining asymptotic formulas for the field, we will use an approach based on the behavior of integrands near branch points of the integrals describing the field. For that we will transform the path of integration into the plane of the complex variable m . The following identities for Bessel's functions will be of use:

$$\begin{aligned} 2J_0(x) &= H_0^{(1)}(x) + H_0^{(2)}(x) \\ \text{and} & \\ H_0^{(2)}(x) &= -H_0^{(1)}(-x) \end{aligned} \quad (\text{Eq. 12})$$

where $H_0^{(\)}$ is the Bessel function of the third kind (see Abramovitz and Stegun, 1964, p. 358).

Making use of Eq. 12, Eq. 6 can be rewritten as:

$$A_z^* = \frac{M}{4\mu} \int_{-\infty}^{\infty} F(m^2) m H_0^{(1)}(mr) dm, \quad (\text{Eq. 13})$$

where $d = 0$ and

$$F(m^2) = \frac{1}{m_0 + \frac{m_1}{R_n}} \quad (\text{Eq. 14})$$

For a two-layer sequence beneath the seafloor, the function $F(m^2)$ contains three radicals m_0 , m_1 , m_2 , and corresponding branch points are defined from the relations:

$$m^2 - k_n^2 = 0$$

Taking into account that for $\text{Re} \sqrt{m^2 - k_n^2} > 0$ only one leaf of the Riemann surface is considered, that being the one where all three roots are positive real. These branch points are

$$m = +k_0, \quad m = +k_1, \quad m = +k_2$$

and the path of integration is drawn in the upper half-plane of m around these branch points as shown in Fig. 5. Let us consider the case in which $\rho_0 < \rho_1 < \rho_2$, and we will assume that the influence of poles is negligible when the separation r significantly exceeds the skin-depth δ_0 in the upper layer. This assumption is supported by comparison of results obtained from numerical integration along the real axis m and in the complex plane m . Our assumption about poles permits us to represent Eq. 13 as the sum of three integrals along appropriate cuts so that we have

$$A_z^* = \frac{M}{4\pi} \left\{ \int_{i\infty}^{k_0} F(m^2) m H^{(1)}(mr) dm + \int_{i\infty}^{k_1} F(m^2) m H^{(1)}(mr) dm + \int_{i\infty}^{k_2} F(m^2) H_0^{(1)}(mr) dm \right\} \quad (\text{Eq. 15})$$

The integrals are evaluated by expanding the kernel function $F(m^2)$ in a power series of terms in n_0 , n_1 , and n_2 . This permits an approximate evaluation of Eq. 15 in terms of elementary transcendental functions, rather than requiring a numerical evaluation of the indicated Hankel transform in Eq. 15--a procedure which is inherently imprecise. For two layers in the subsea (a layer with a lower half-space), the result is:

$$A_z^* = \frac{M}{2\pi r^3} \frac{\text{sech}^2 k_{21} h_1}{(k_2^2 - k_0^2)} \frac{e^{-k_2 r}}{1 + \frac{k_{21}}{k_{20}} \tanh k_{21} h_1} (1 + k_2 r) \quad (\text{Eq. 16})$$

$$\text{if } \frac{r}{\delta_0} \gg 1, \frac{r}{h_1} > 1, \sigma_0 \gg \sigma_2$$

where

$$\text{Re } k_{21} > 0, \text{Re } k_{20} > 0, k_{21} = \sqrt{k_2^2 - k_1^2}, k_{20} = \sqrt{k_2^2 - k_0^2}$$

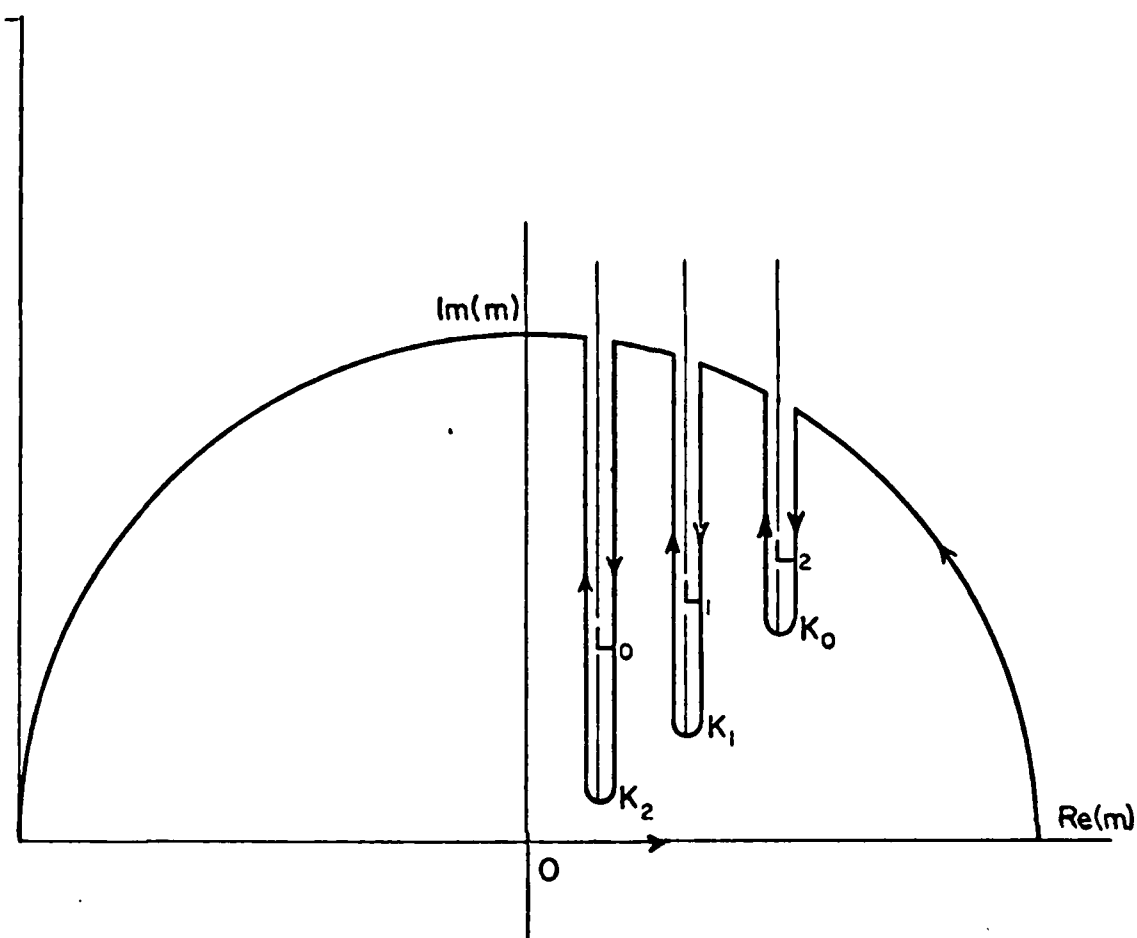


Figure 5. Path used in integration of Eq. 15.

This expression for the field is the product of two terms. The first term corresponds to the field at the interface of two uniform half-spaces with conductivities σ_0 and σ_2 .

$$\frac{M}{2\pi r^3 (k_0^2 - k_2^2)} e^{-k_2 r} (1 + k_2 r)$$

The second multiplier is

$$= \frac{\sec^2 k_{21} h_1}{1 + \frac{k_{21}}{k_{20}} \tanh k_{21} h_1^2},$$

which is a function of the electrical parameters describing the medium and which does not depend on the separation r .

In other words, in the far zone, the influence of the thickness h_1 remains the same regardless of the separation. It is obvious that, as the skin-depth in the layer becomes significantly larger than the thickness, the second term tends to unity; and the magnitude of the field at an observation site coincides with that for a uniform half-space with conductivities σ_0 and σ_2 . In the opposite case, as the skin-depth δ_1 becomes less than h_1 , the second term is proportional to e^{-2h_1/δ_1} . This consideration leads us to the conclusion that the asymptotic expression in Eq. (16) describes the electromagnetic field, which arrives at an observation site along the path B shown in Fig. 6.

Assuming that conductivity decreases progressively with depth in the seafloor with increasing frequency, the relative contribution of the field component arriving along path B increases when the condition $r > 2 h_1$ holds. Because this part of the electromagnetic field carries most of the information about the geoelectrical parameters, one can appreciate the fact that the depth of investigation becomes greater with

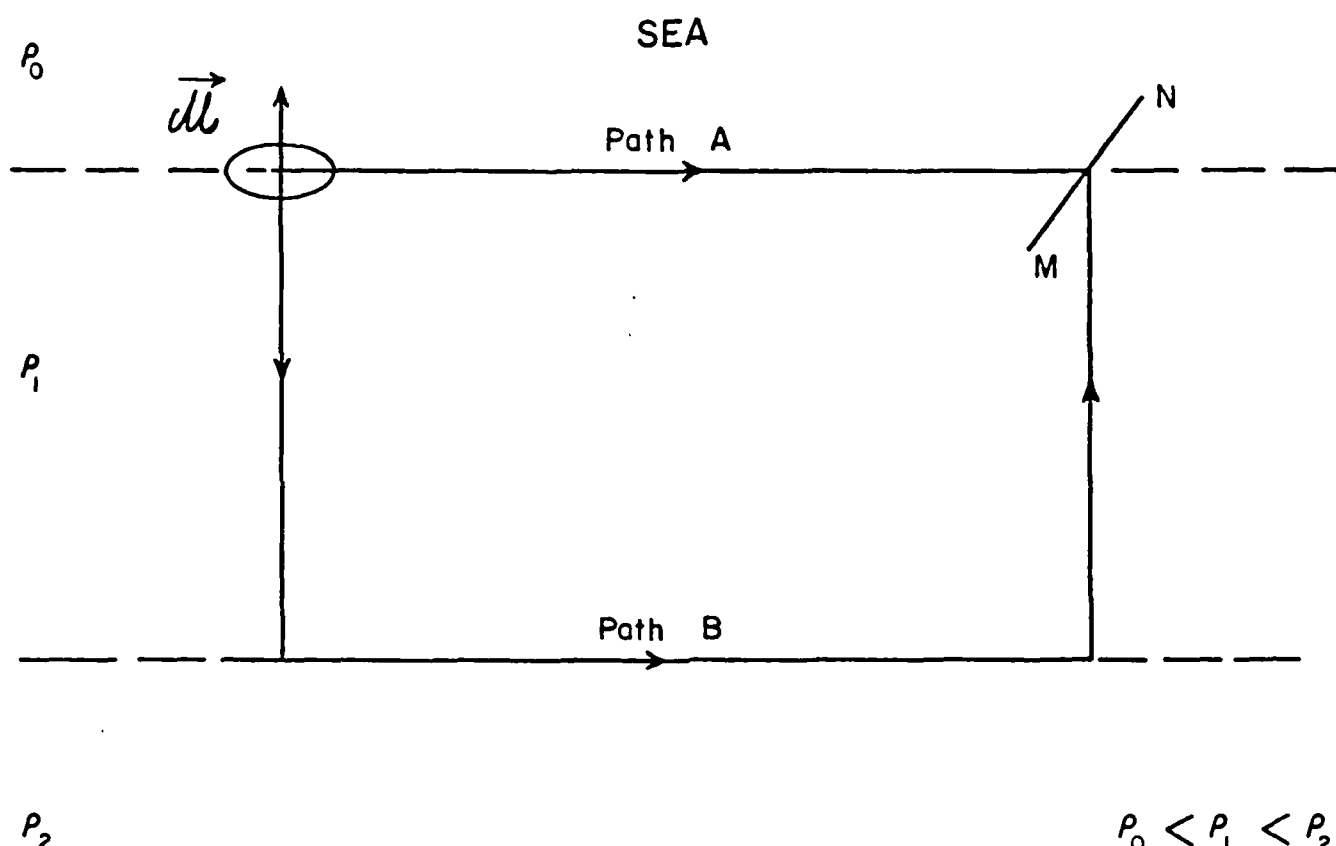


Figure 6.

Definition for alternate paths for the electromagnetic field to follow in coupling between a loop transmitter and a wire receiver on the seafloor. Medium 0 is the ocean, medium 1 is a layer beneath the seafloor with resistivity ρ_1 , and medium 2 is a lower region with resistivity ρ_2 .

an increase of the frequency, even though the magnitude of the field decreases over the same range. The presence of highly conductive sea water strongly attenuates that part of the energy which does not carry information about the geoelectrical parameters of the seafloor, and so the relative influence of the useful part of the signal propagating along the path B on the total signal at the receiver increases. This fact demonstrates the fundamental difference between measurements made on the Earth's surface, where a very strong field traveling over path A overwhelms the signal along path B and at the seafloor. Thus, an analyses of the field in the far zone ($r > 2 H_1$), when the separation r is greater than the skin-depth in sea water, has shown that the influence of deep layers is significant; and this range of parameters is the most important from a practical point of view.

A series of coupling curves for a magnetic dipole source and electric field receiver are shown in Figures 7 through 11, illustrating the properties of such curves. The first (Figure 7) is a plot of normalized electrical field strength as a function of normalized frequency,

$$r/\delta_0 = \left(\frac{r^2 \omega \eta \sigma_0}{2} \right)^{1/2}$$

For this one case, the transmitter and receiver lie a distance $1/16 r$ above the seafloor. The various curves indicate the results to be obtained for seafloor conductivities ranging from $1/2$ to $1/32$ that of sea water, or from 0.125 to 2 mhos per meter.

The electric field has been normalized by dividing by the value which would be observed if no bottom were present. In such a case, for r/δ_0 more than unity, the field strength decays nearly exponentially. Thus, the extreme rise shown by the curves in Fig. 8 for high frequencies does not mean that the field increases in strength but, rather, that it falls less rapidly with frequency when the bottom is present. This enhancement of the otherwise rapidly decreasing electric field becomes significant at scaled frequency values of 2 to 3 . To study the bottom, it is necessary to use frequencies greater than some ω_{\min} given by

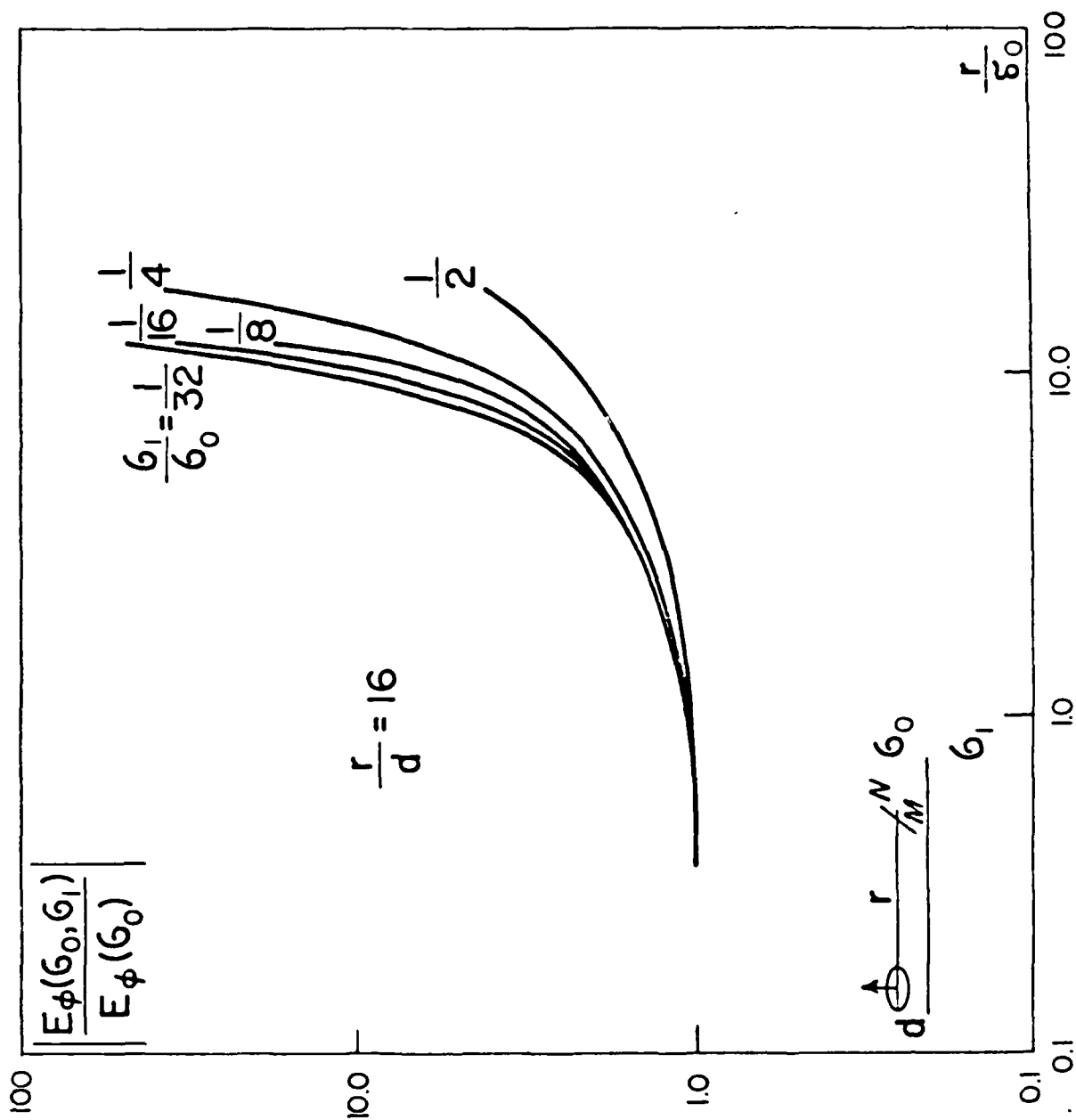


Figure 7.

Coupling curves for an array situated at a distance of $1/16$ r above the seafloor. Each curve represents one value of seafloor conductivity. The electric field is normalized to the value for the array when no bottom is present. The variable r/δ_0 is scaled frequency, defined as $\omega^{1/2} (r^2 \mu \sigma / 2)^{1/2}$.

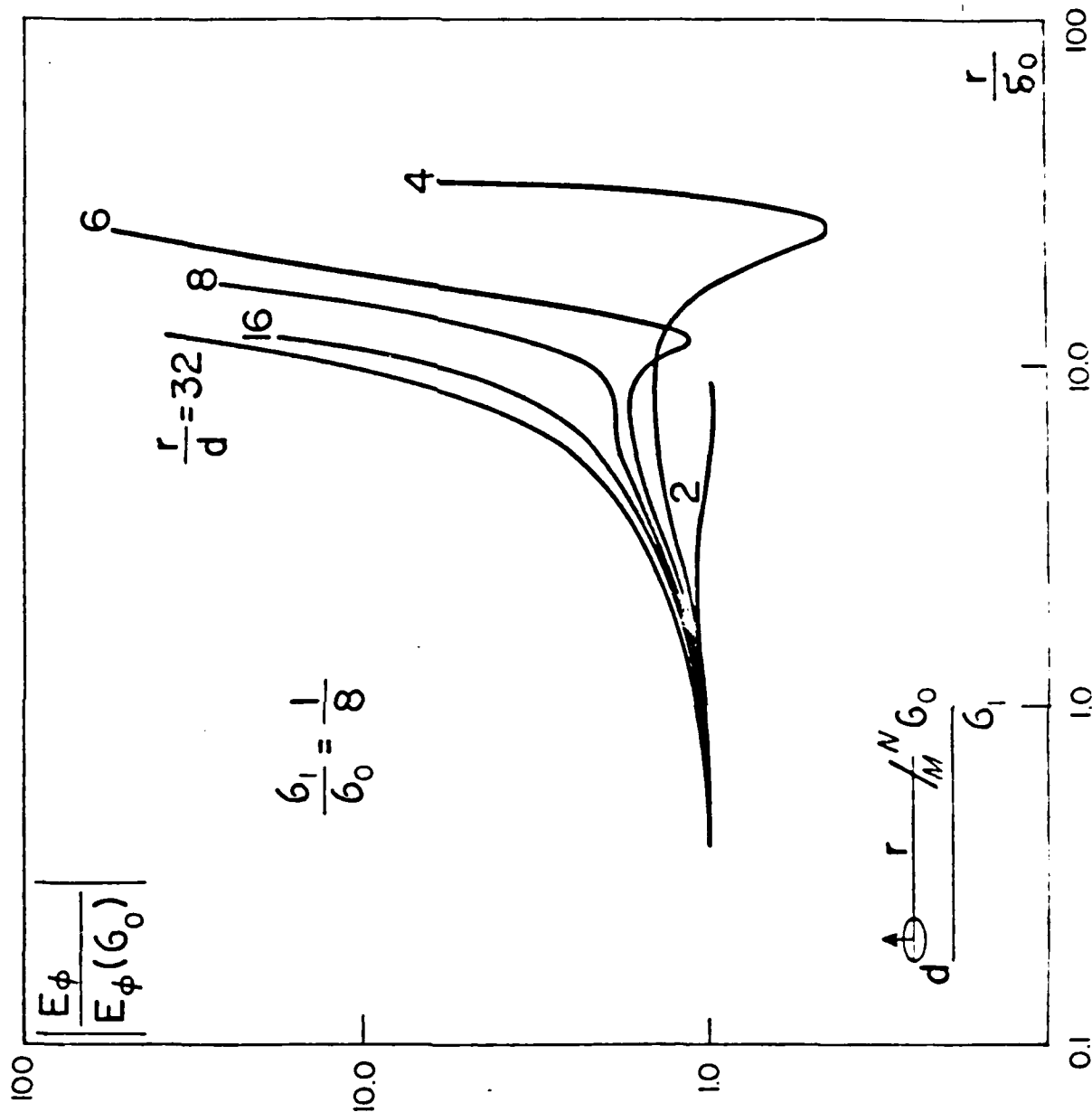


Figure 8. Coupling curves showing the effect of elevation of the system above the seafloor. The frequency and electric field strength have been normalized in the same manner as in Fig 7.

$$\omega_{\min} = \frac{20}{r^2 \mu \sigma_0} = \frac{2 \times 10^8}{4 \pi r^2} \quad (\text{Eq. 17})$$

The elevation of the array above the seafloor is an important parameter. Fig. 8 shows a group of curves for which all parameters are the same except this elevation, which is allowed to vary from 1/32 to 1/2 of the distance r . It should be noted that the electric field has been normalized not to that in the open sea but, rather, to that observed on a uniform bottom with the conductivity σ_1 . Thus, these curves represent a multiplicative modification to a curve such as shown in Fig. 7 or 8. As elevation increases, the effect of the seafloor becomes weaker and is shifted towards higher frequencies. When the elevation becomes as great as half of r , the effect of the bottom becomes negligible. The conclusion to be drawn is that the EM method will work only if the equipment is in almost direct contact with the seafloor.

Fig. 9 shows coupling curves for a more realistic model of the sea floor--one in which resistant rock is covered by a thin layer of sea water saturated sediment, having a conductivity of 1/8 that of sea water, or 0.5 mhos. The hard seafloor is assumed here to be insulating. The various curves indicate mud-layer thicknesses ranging from 1/32 to 1/2 the length of the array.

The effect of the thin conductive layer is very similar to the effect caused by raising the system above the seafloor. The contribution of the resistive rock beneath the mud is subdued as the mud thickness becomes greater and virtually disappears when the mud thickness amounts to half the array spacing.

Fig. 10 shows coupling curves for the same case, that of a mud layer covering a resistive lower region; but all parameters are fixed except the conductivity in the lower region. The electric field as plotted has been normalized by referring it to the electric field that would be observed on a uniform bottom with a conductivity of 1/8 that of sea

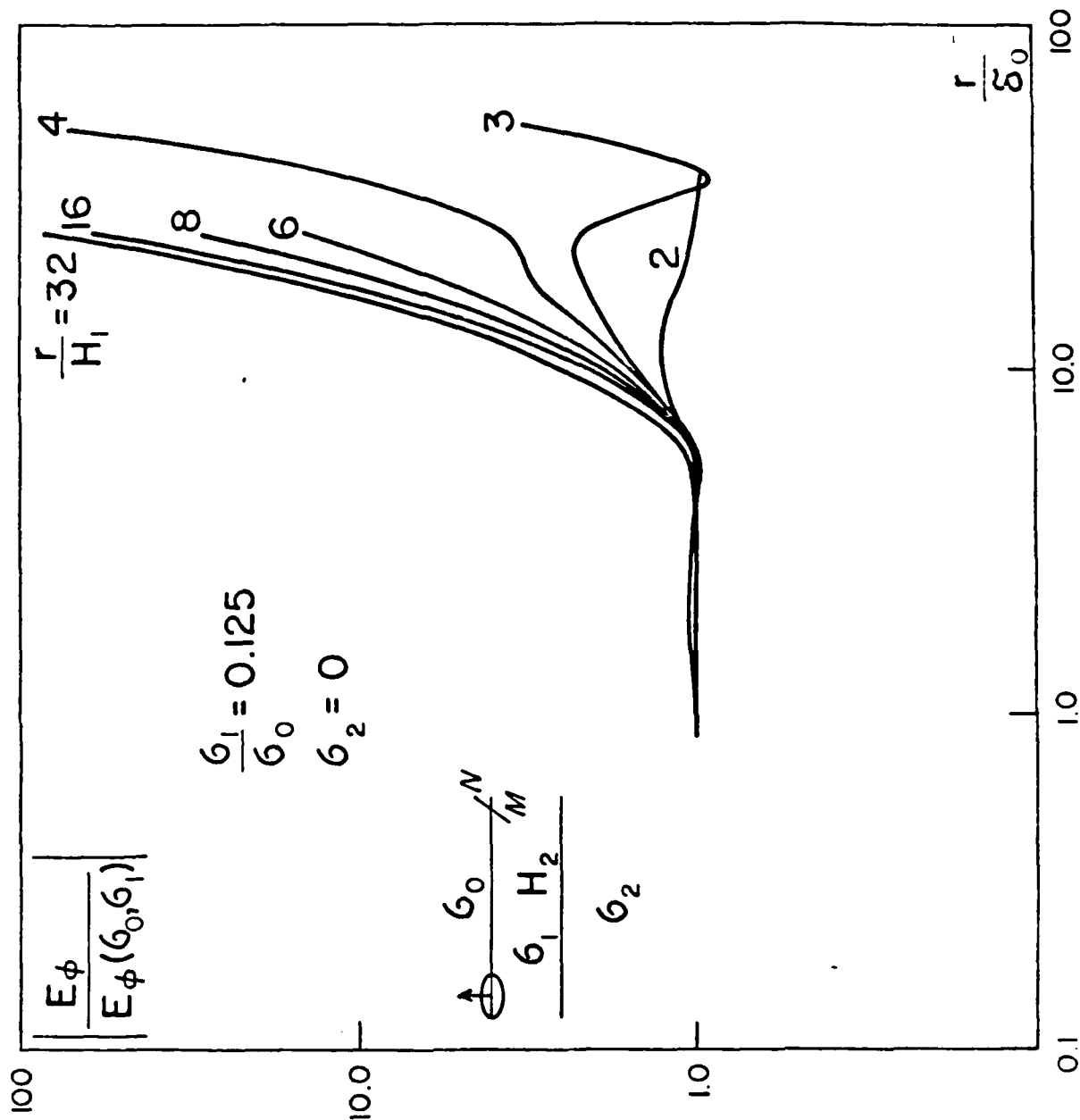


Figure 9. Coupling curves showing the effect of a thin layer of conductive sediment (0.5 mho/m) on the seafloor. The frequency has been normalized in the same way as Fig. 7, but the electric field has been divided by a reference electric field that would be observed on a uniform bottom with conductivity σ_1 .

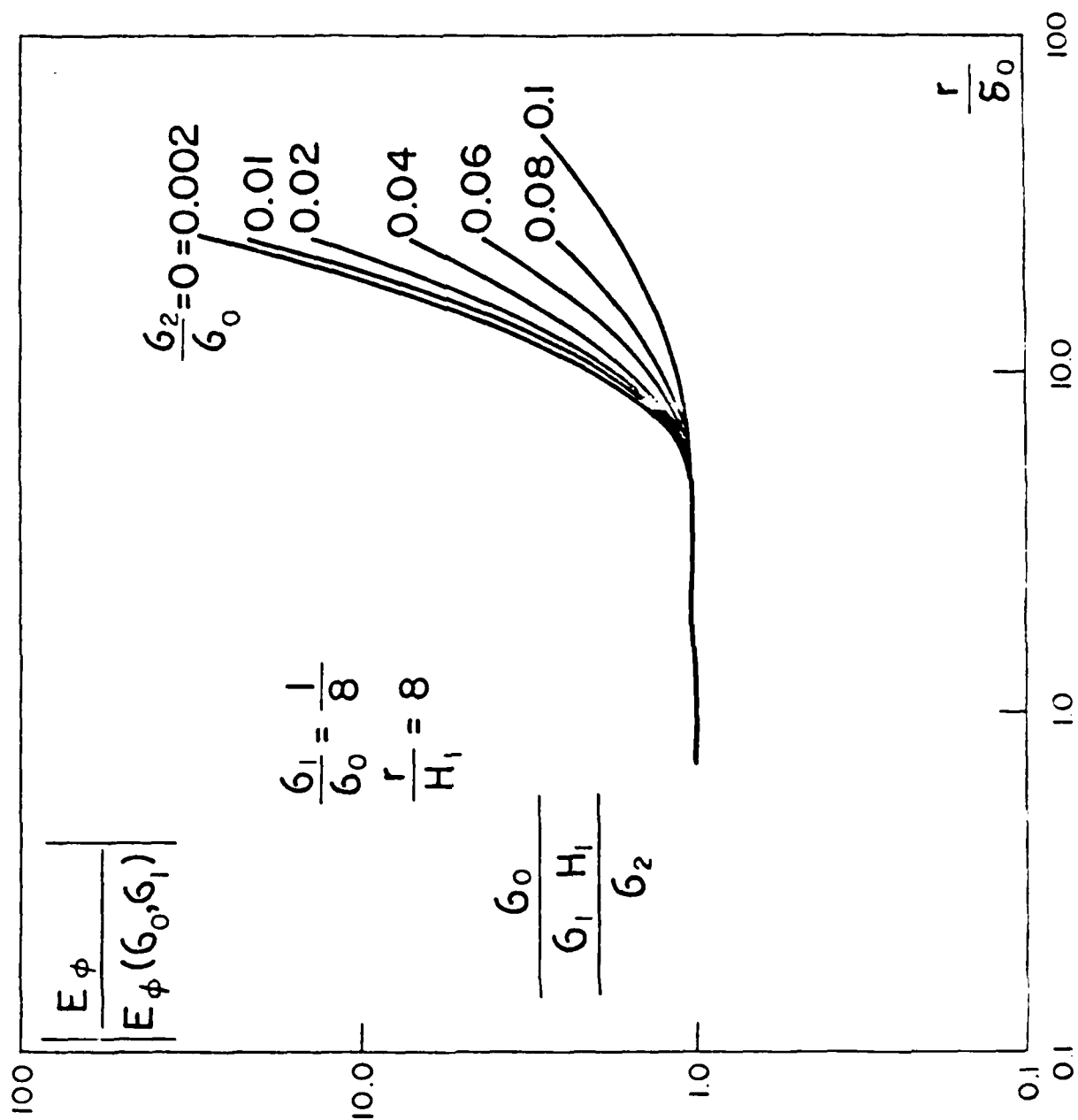


Figure 10. Coupling curves for the case in which a thin conductive mud layer covers a resistive seafloor. The electric field and frequency have been scaled as in Fig. 9.

water, or 0.5 mho/m. This normalization removes the effect of the mud layer from the curves and shows that the effect of the lower medium does not begin to manifest itself until scaled frequency values reach 10 or more. These curves reinforce the concept developed earlier: by using progressively higher frequencies, progressively greater penetrations into the seafloor. This is, of course, a contradiction to the experience we have with EM soundings made on dry land.

FIELD TRIAL

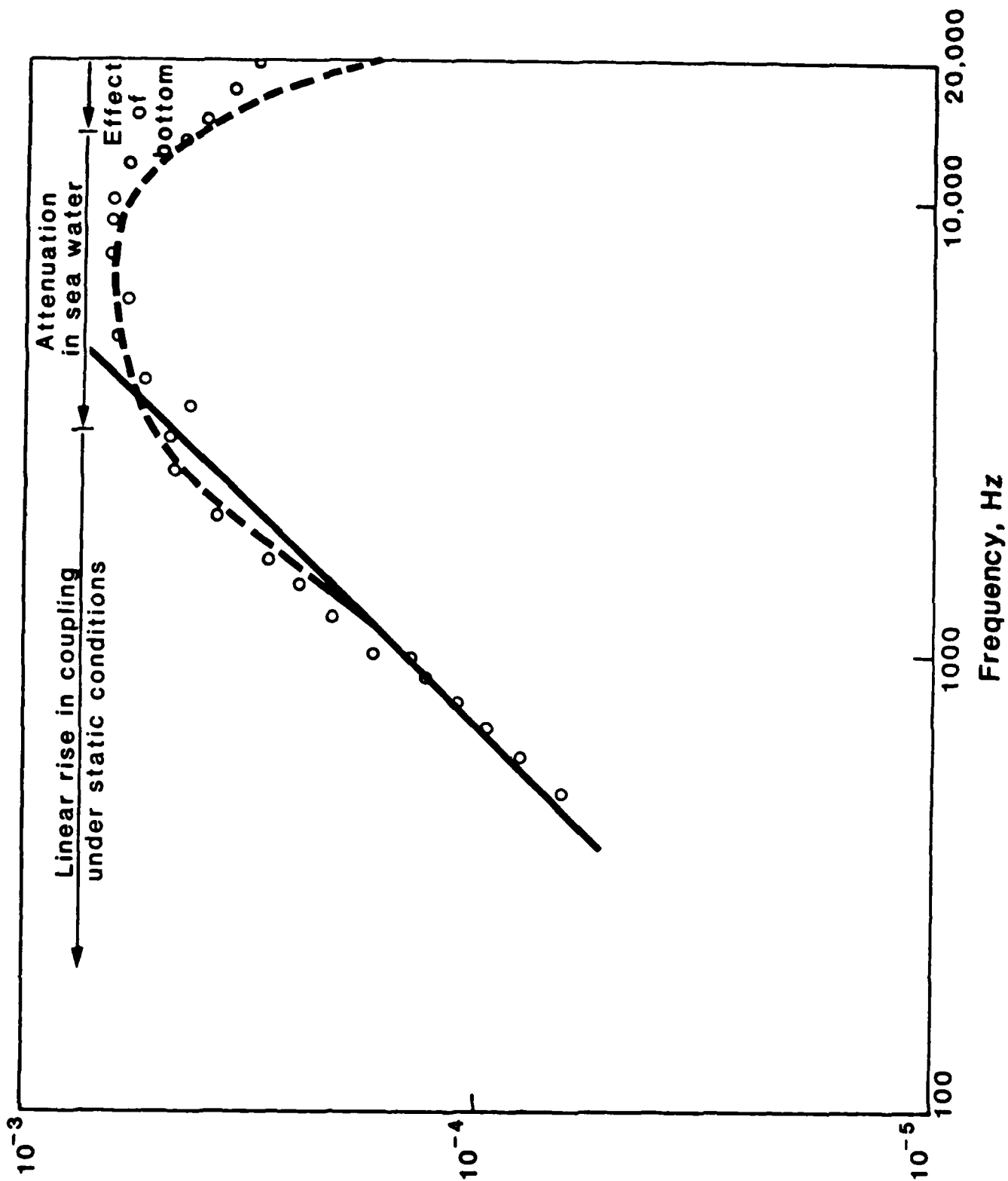
The results of the theoretical analysis are somewhat curious, running counter to our intuitive understanding of how electromagnetic fields are used in probing the Earth. To test the predicted response of measurements on the seafloor, we carried out a small-scale survey with the help of the Navy Postgraduate School and Prof. Otto Heinz.

Measurements were made from the Research Vessel, Acania, anchored at various locations in Monterrey Bay. As a transmitter, we used a small square coil, 1.82 meters on a side, carrying two turns of wire. The coil was energized with an audio oscillator, providing 1 to 2 amperes of current at selected frequencies between 200 Hz and 20,000 Hz. The transmitter coil was lowered from the bow of the Acania in water 15 to 20 meters in depth. The oscillator was operated in the wardroom, using a coax cable to carry energy to the transmitter.

The receiver coil was of the same dimensions, but was wound with 244 turns of lighter-weight wire, and was connected by coax cable to a turnable voltmeter, also in the wardroom of the Acania. The separation between transmitter and receiver was nominally 20 meters.

Several attempts were made to measure a spectrum of mutual coupling, with the most successful set of data being shown in Fig. 11. The mutual coupling is the ratio of received voltage to transmitted current, with no normalization applied.

At low frequencies (up to about 2 KHz), the coupling increases nearly linearly with frequency. This behavior is the static behavior expected at low frequencies when induction in sea water is negligible. At higher frequencies, from 2 KHz to 10 KHz, the coupling reaches a maximum and begins to decrease. Over this range, the induction is significant only in the sea water; for no induction in the seafloor, the coupling curve should follow the dashed line on Fig. 11. At frequencies above 15 KHz, which according to Fig. 17 corresponds to the minimum frequency for



Mutual Coupling, OHMS

Figure 11. Mutual coupling data set obtained in Monterrey Bay in August 1982. Water depth was 15 to 20 meters. Transmitter-receiver separation was about 20 meters.

probing the bottom at a coil separation of 22 meters, the coupling data begin to decrease more slowly with frequency than would be the case of no induction in the seafloor.

For a determination of seafloor conductivity with accuracy, it would be necessary to trace the coupling to frequencies that are several times higher. This could not be done with the equipment used for the experiment. The rapid flexure of the coupling curve at frequencies above 15 KHz indicates that the contrast between sea water and seafloor conductivity is sharp, probably an order of magnitude or more; hence, the seafloor resistivity is probably 2.5 ohm-meters or more.

SUMMARY AND CONCLUSIONS

A theoretical analysis has indicated that electromagnetic sounding has a unique capability among the electrical sounding methods for measuring the conductivity of the interval immediately beneath the seafloor. The more conventional sounding methods have a pronounced blind zone for depths beneath the seafloor comparable to the depth of water. On the other hand, EM sounding appears to offer resolution in this range which is not available even in conventional applications on dry land. A paradox exists in that, with measurements made on the seafloor, increasing penetration is obtained with higher frequencies.

A field trial in shallow water at Monterrey Bay using very simple equipment confirms the theoretical predictions.

A practical system would use wider separations than that employed in the Monterrey Bay experiment. A system which seems practical by scaling up the prototype system would employ a separation of 200 meters, a separation great enough to permit probing to 100 meters beneath the seafloor. In increasing the spacing by a factor of 10, it is necessary to decrease the threshold frequency by a factor of 10^2 and to increase the source moment x receiver moment/sensitivity factors by 10^4 . The source moment can be increased by a factor of 10^3 easily by increasing the number of turns by 20, the amount of current by 20 (to about 100 watts power dissipation), and the area by a factor of 2.5. The receiver moment can be increased by a factor of 10 by increasing the area by 2.5 and the number of turns by 4. The threshold sensitivity of the receiver can easily be improved from the 100 μ V level, used in the Monterrey Bay experiment, to 1.0 μ V to provide some additional capability beyond that needed to achieve a separation of 200 meters.

The frequency range of interest would be from 150 Hz to 15 KHz at the longer separation.

Deploying two coils at the greater separation requires more complex operations. One approach that seems feasible is to deploy the receiving coil with a buoy to the surface carrying a data link. The ship would move approximately 200 meters away and deploy the transmitter coil. Knowledge of the exact separation is unnecessary, because as shown in the field trial in Monterrey Bay, it can be determined independently from the data.

Development of a system larger by another factor of 10 may be feasible but would require extensive engineering development. Such a development should probably not proceed until a mid-scale system such as that described in the preceding paragraph provides enough results to demonstrate the utility of the method.

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